DECADE QUAD DESIGN AND TESTING STATUS

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ABSTRACT

The Decade Quad (DQ) is a high power generator that will be built at Arnold Engineering Development Center (AEDC) in Tullahoma, Tennessee by the Defense Special Weapons Agency (DSWA). The DQ will consist of four independent command triggered pulsed power modules. The building at AEDC has been completed and has the capacity to accommodate up to four DQ machines for a total of 16 modules. Two full power modules (DM1 and DM2) have been built and tested to verify the Decade design at PRIMEX Physics International. Each module consists of a 570 kJ Marx generator that pulse charges a water transfer capacitor. The transfer capacitor discharges into a water output line through an array of six parallel triggered gas switches. The water output line then pulse charges the inductive store/opening switch pulse compression stage. When the opening switch opens, the inductive store discharges into an electron beam bremsstrahlung diode load.

Two full power prototype modules have been built and tested into electron beam bremsstrahlung loads. Over 3500 machine shots have been taken on the two modules. The measured pulsed power and the radiation output performance from the single module has been used to predict the radiation output from the Decade Quad. The new machine will be capable of producing 16 krads(Si) over a 2250 cm^2 test area with a 47 ns radiation pulse width.

A future upgrade of the Decade Quad is planned to provide the capability to drive imploding plasma radiation loads for soft (1-5 keV) x-ray production. A design sketch of the Decade Quad pulsed power configuration for driving a plasma radiation source has been completed. The Decade Quad circuit model has been coupled to an imploding load model to quantify the effects of the I x Ldot voltage on the pulsed power system and to estimate the kinetic energy delivered to the load. A range of implosion times and inductances were assessed to determine the optimum low risk design configuration.

INTRODUCTION

The Decade Quad facility will be the first high power x-ray simulator in the United States to be built using inductive store/opening switch (IS/OS) technology for the final phase of pulse compression. The advantage of using IS/OS technology is that the energy is stored magnetically at high density near the load providing for high power, short pulse discharge once the opening switch opens. The plasma opening switch (POS) has been used for pulse compression and power amplification in a variety of inductive energy storage systems with conduction times ranging from tens of nanoseconds to over one microsecond (Reference 1-8). The use of IS/OS technology rather than the conventional capacitive storage technology becomes critical for large (>50 TW), short pulse (20 ns), electron beam (bremsstrahlung x-ray) generators.

The bremsstrahlung load has been extensively tested on a single module and the radiation measured on several shots. The projected radiation performance of the four module Decade Quad machine has been determined from the single module results. The initial operating condition for the new machine will be in this bremsstrahlung mode.

The Decade Quad will also be capable of driving plasma radiation source (PRS) loads with some modification to the front-end (tube and MITL) configuration. Scoping studies to determine the sensitivity of the PRS radiation

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The Decade Quad (DQj is a high power generator that will be built at Arnold Engineering Development Center (AEDC) in Tullahoma, Tennessee by the Defense Special Weapons Agency (DSWA). The DQ will consist of four independent command triggered pulsed power modules. The building at AEDC has been completed and has the capacity to accommodate up to four DQ machines for a total of 16 modules. Two full power modules (DM 1 and DM2) have been built and tested to verify the Decade design at PRIMEX Physics International. Each module consists of a 570 kJ Marx generator that pulse charges a water transfer capacitor. The transfer capacitor discharges into a water output line through an array of six parallel triggered gas switches. The water output line then puke charges the inductive storehpening switch pulse compression stage. When the opening switch opens, the inductive store discharges into an electron beam bremsstrahlung diode load.

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yield to the front-end inductance have been completed. After the Decade Quad is operational in the brems testing mode it will be upgraded to drive PRS loads.

In the remainder of this paper, we will first review the mechanical and electrical description of the Decade Quad facility. The second section will include the single module bremsstrahlung testing results and the predictions of the output from the Decade Quad. The last section will include the projections for the PRS output from the Decade Quad.

DECADE QUAD DESCRIPTION

A sketch of the four module Decade Quad machine is shown in Figure 1. The machine will consist of a single Marx tank with four separate Marx modules. There are four output locations from the Marx tank that will each feed a water insulated transfer capacitor, water output line, vacuum insulator (tube), magnetically insulated transmission line (MITL), and a plasma opening switch (POS)/bremsstrahlung load configuration. Figure 2 shows a top view of the Decade Quad in the building at AEDC in Tennessee. The facility at AEDC has been built to accommodate up to four Decade Quad machines. The initial Decade Quad can be assembled in any one of four locations as shown in this figure.

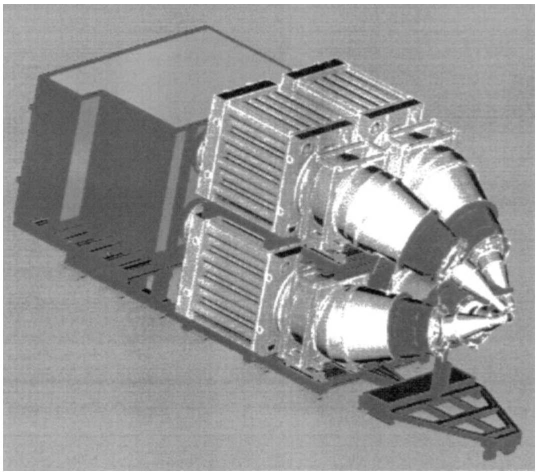


Figure 1. Decade Quad brems configuration.

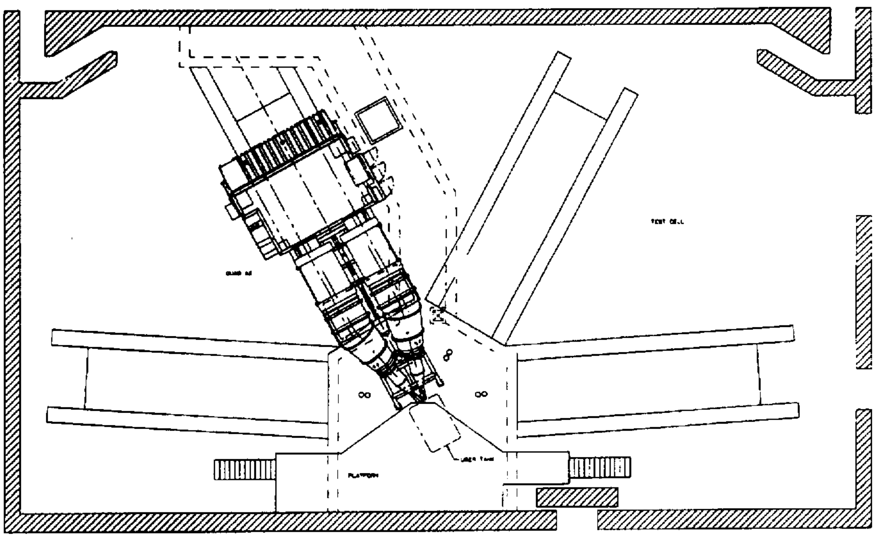


Figure 2. Top view sketch of the Decade Quad in the test facility at AEDC.

A detailed sketch of a single module of the Decade Quad is shown in Figure 3. The pulsed power is initiated by first triggering the Marx generator that then charges the transfer capacitor. The transfer capacitor is discharged by triggering the six output switches and charges the water insulated output line that charges the inductive store/opening switch pulse compression stage. Once the POS opens the inductive store is discharged into the bremsstrahlung load. The circuit model that has been developed in the course of designing and testing the Decade modules is shown in the bottom of Figure 3. A detailed discussion of the pulsed power operation and the comparison with the circuit model was included in a previous paper (Reference 9).

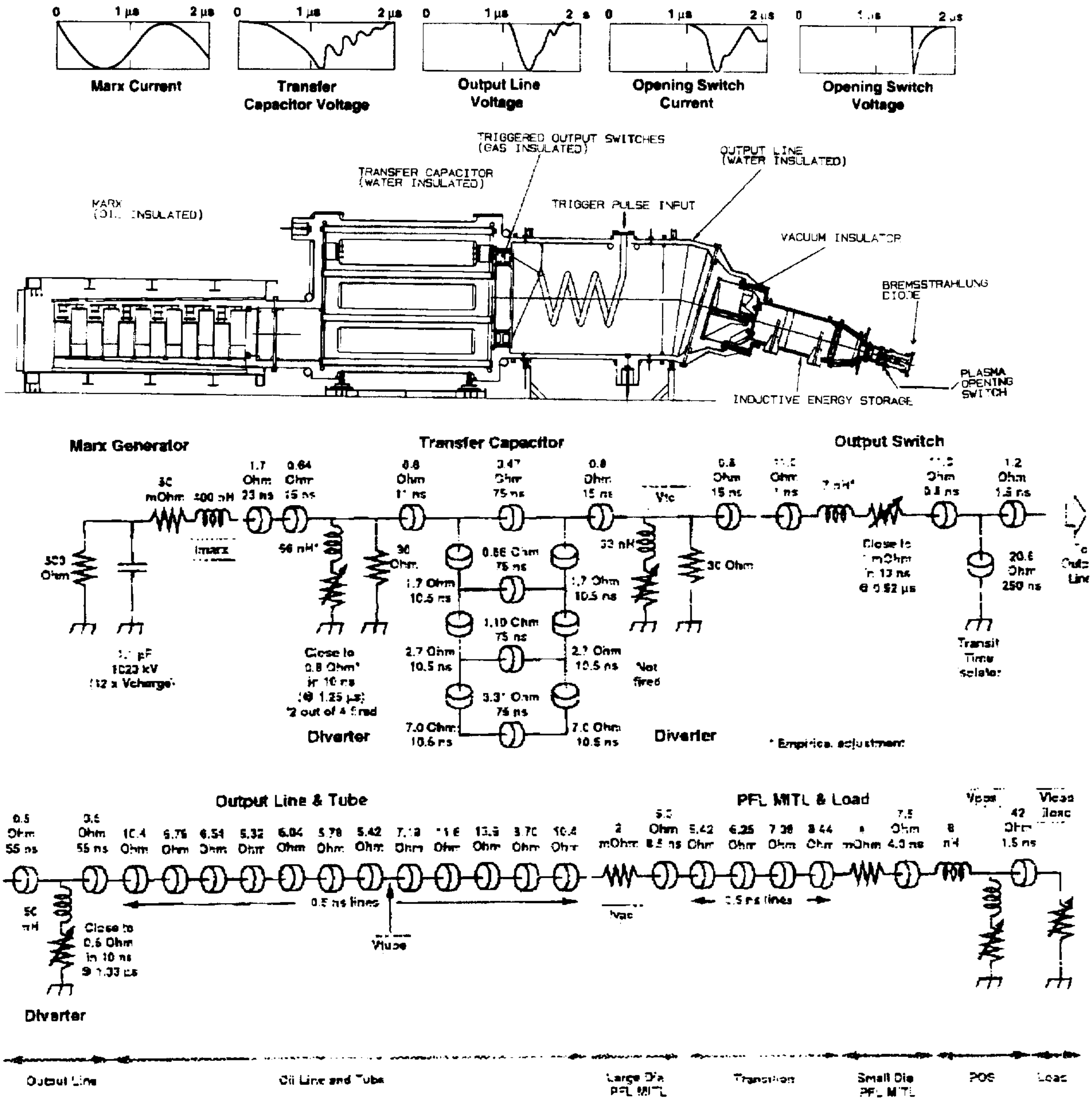


Figure 3. Side view and circuit model of a Decade module.

Table 1 below is a summary of the electrical parameters of the Decade Quad.

Table I. Summary of the subsystem parameters (Brems configuration).

- Marx
  - Energy stored at ± 85 kV is 2.3 MJ with 570 kJ/module
  - nH inductance/module
  - Erected capacitance = 1.1 μF/module
  - Erected voltage = 1.0 MV
- Transfer Capacitor (one of four modules)
  - Water insulated
  - Length = 139 ns one way
  - Capacitance = 470 nF
  - Peak voltage = 1.4 MV
  - Impedance = 0.3 Ω
  - Output switches ⇒ 6 - parallel, SF_6 insulated, single stage, triggered gas switches
- Output Line (one of four modules)
  - Water insulated
  - Length = 110 ns one way
  - Impedance = 0.54 Ω
  - Capacitance = 200 nF
- Oil/Vacuum Insulator (tube)
  - 16 insulator/gradient ring stacked configuration
  - Insulator stack height = 35 cm
- Vacuum Inductive Store
  - Length = 3 m tube to plasma opening switch
  - Impedance is 5.0 Ω at the tube tapering down to 7.5 Ω
- Plasma Opening Switch
  - Plasma source is 24, 0.25 inch coaxial cable guns
  - Anode diameter = 7.25 inches
  - Cathode diameter = 3.5 inches
- Bremsstrahlung Diode Load
  - Pinched beam diode on each module
  - Cathode diameter = 5 inches
  - Ta Converter

PULSED POWER PERFORMANCE AND PREDICTED BREMSSTRAHLUNG RADIATION OUTPUT

Two prototype modules (Decade Module 1 (DM1) and Decade Module 2 (DM2)) are in operation at PRIMEX Physics International. They were built by DSWA to demonstrate the pulsed power and radiation load technology prior to building the Decade Quad facility at AEDC. The two modules are in separate radiation cells and can be operated independently. DM1 has been on-line for three years (over 3000 shots) while DM2 has been on-line for over a year and has accumulated over 500 shots. Both modules have demonstrated reliable and reproducible pulsed power operation as evidenced in Figure 4. This figure shows a 55 shot overlay of the opening switch conduction current on DM1. The standard deviation in the conduction current is less than 2% during the charging of the inductive store. The deviation in the peak current is due to controlled changes in the opening switch conduction time in an effort to optimize the system performance. The overall timing jitter to achieve 1.1 MA is ±4 ns.

55 Shot Overlay for a Range in Conduction Times

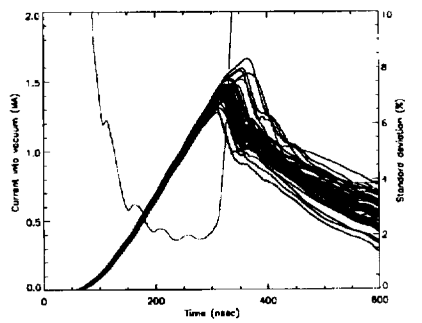


Figure 4. The current delivered to the opening switch is very reproducible.

DM1 has been used as the primary test facility for demonstrating the radiation performance from a single Decade module. The radiation performance from DM1 on a sequence of several shots is used to predict the output from the four module Decade Quad (DQ) machine. Note that each of the four modules of DQ is completely independent of the other modules, therefore knowing the radiation pattern and standard deviation in the radiation output pulse timing from a single module provides a database for predicting the output from the four module machine.

The method for predicting the dose (Si) radiation output for the DQ from the single module output performance begins by making radiation measurements on DM1 for a sequence of at least eight shots. The radiation diagnostics include a calibrated silicon PIN diode to measure dose rate (Si) at 1 m from the source, an array of TLDs (CaF and LiF) at the position of the planned test plane (about 13 cm from the source), a filtered depth dose stack of TLDs at 1 m, and a seven channel filtered PIN array to measure the end point energy of the radiated spectrum. A sketch of the POS/diode configuration and a sample of the dose profile as measured at the test plane for a sample shot is shown in Figure 5. The details of the POS performance and method of optimization was discussed in a separate paper at this meeting (Reference 10).

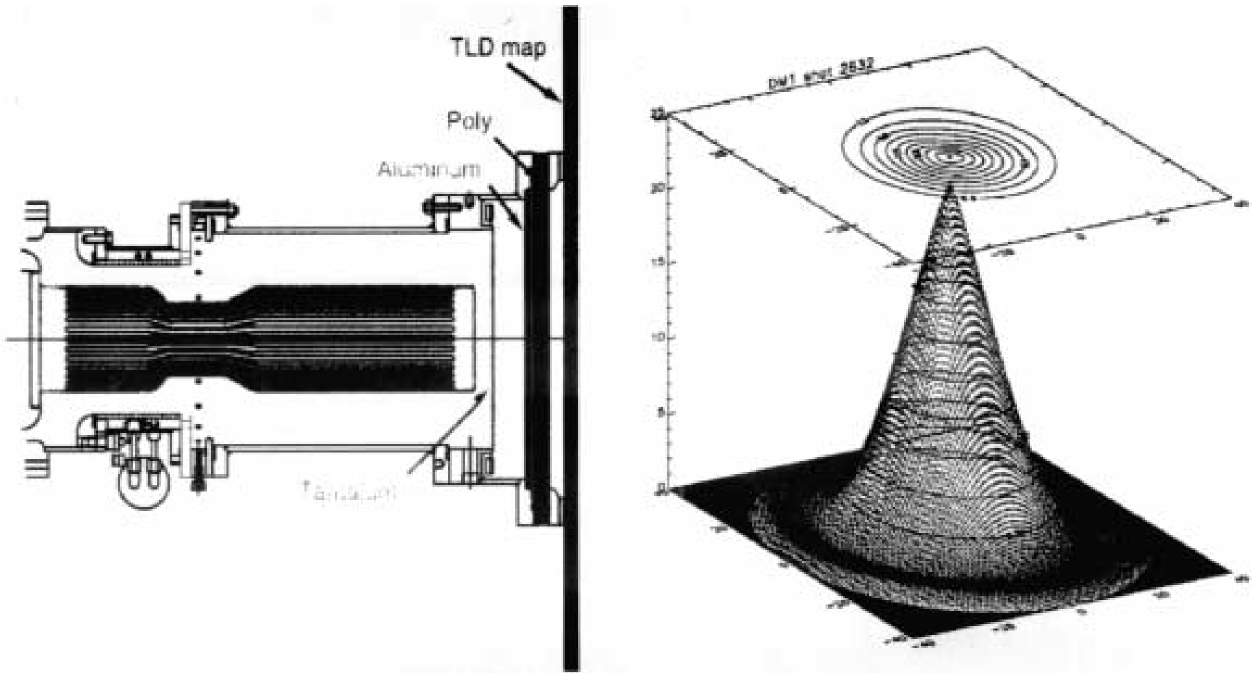
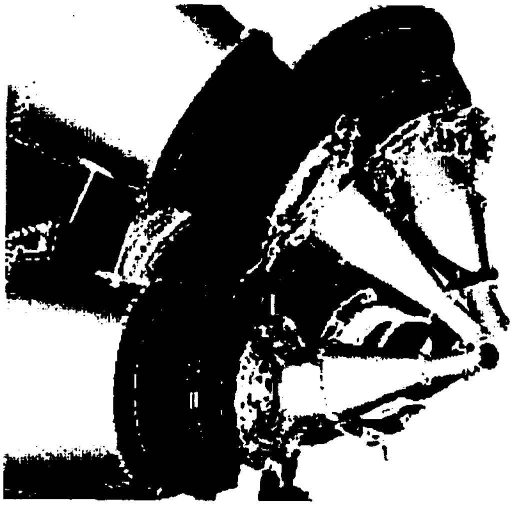


Figure 5. Front end with dose map.

The method of processing the single module radiation data begins by first entering the measured dose maps at the test plane from each shot into the computer and converting the measured dose (LiF) to dose (Si) using the silicon PIN diode and TLD measurements at 1 m. The next step in processing the data is to determine the average peak dose and standard deviation in the amplitude, position and full width at half maximum of the dose profile for a sequence of at least eight shots. The final step in the process of predicting the output from DQ is to use these measured average parameters to construct the dose profile from the four modules in the planned mechanical configuration of the diodes as shown in Figure 6. This figure shows the planned front-end configuration of the Decade Quad and an example of a computer generated dose profile from a sample shot on DQ based on a sequence of nine data shots on DM1.



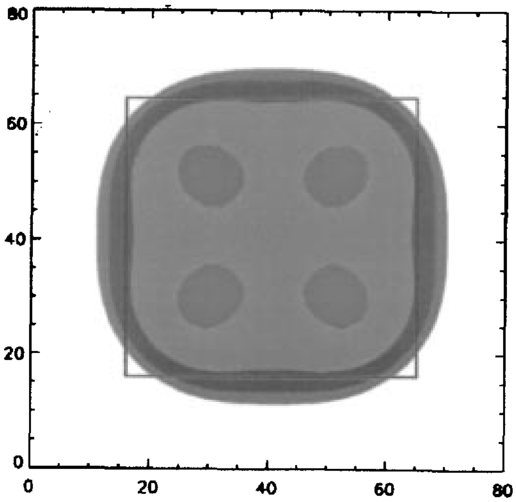


Figure 6. Optimized diode configuration for the Decade Quad.

Using the measured standard deviation in performance from DM1 as discussed above, a sequence of 100 sample shots on the Decade Quad facility was generated on the computer. The projected DQ performance on these 100 shots is shown in Figure 7. The top plot shows the area averaged dose (Si) over a 2250 cm^2 test plane for the 100 shot sample set. The average DQ dose on these 100 shots is 16.5 krads(Si), with a standard deviation of 8.5%. The middle plot shows the variation in the 2:1 testing area on the 100 sample test shots. The last plot is the product of the first two plots, the dose X area. The projected standard deviation in the dose area product is 9.3%. The predicted dose rate 1 m from the source on these 100 sample DQ shots is shown in Figure 8. The average FWHM of the dose rate on these 100 shots is 47 ns.

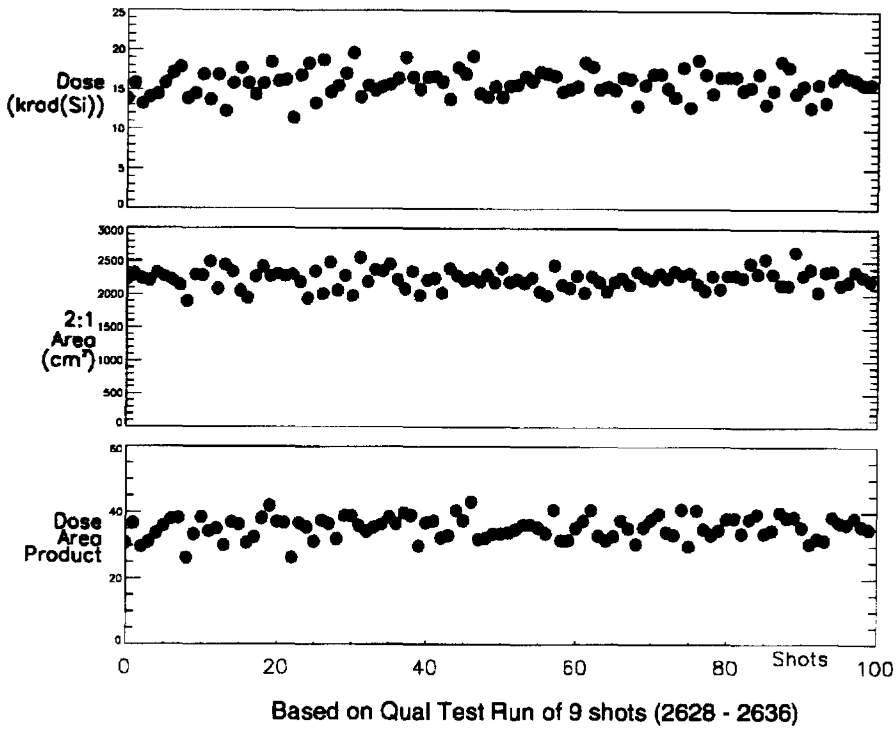


Figure 7. Decade Quad predicted performance on a 100-shot run based on the single module test data.

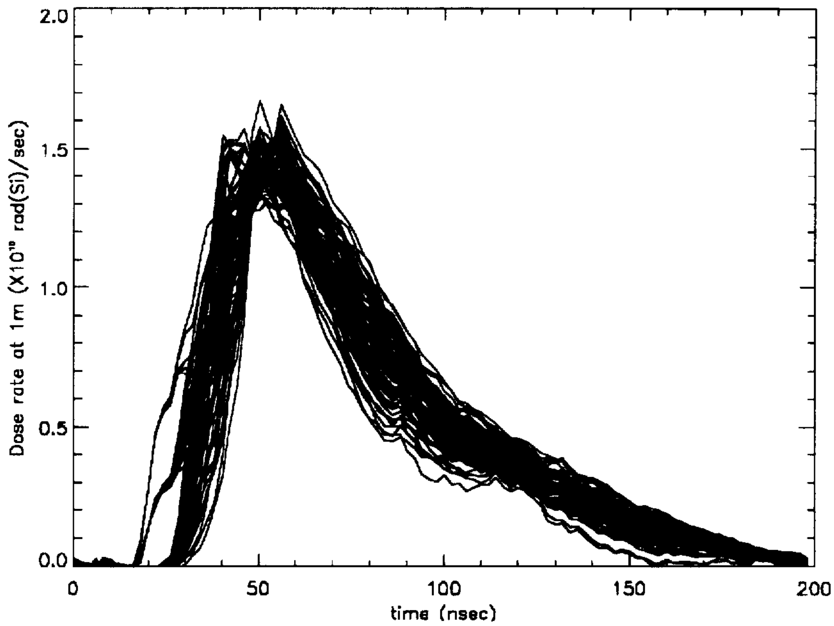


Figure 8. The predicted DQ dose rate for 100 simulated shots shows reproducible radiation performance.

THE DECADE QUAD PLASMA RADIATION SOURCE CAPABILITY

In this section we will present a design for the Decade Quad front-end that is capable of driving plasma radiation source (PRS) loads. A pulsed power system design has been completed that utilizes most of the planned bremsstrahlung front-end (vacuum insulators and MITLs) to drive the PRS load. The method of design is to use the circuit model for the machine shown in Figure 3 coupled to a model with a vacuum convolute (Double-EAGLE post-hole style convolute) and an imploding plasma load with a changing inductance in time. The MITL is assumed to be well insulated if the load impedance divided by the MITL geometric impedance (Zload(V/I)/Z MITL) is less than .33. The initial radius of the PRS load is chosen to achieve a final implosion velocity of 60 cm/usec for the selected implosion times (either 400 ns or 250 ns). The final implosion velocity (60 cm/usec) is chosen to simulate the correct inductance as a function of time that is relevant to achieving the kinetic energy per ion appropriate for producing efficient k-line radiation for Argon. The implosion is completed when a compression ratio (initial /final radius) of 10 to 1 is achieved. The load length for these calculation was 4.0 cm. The Argon k-line yield estimates are based on scaling from Double-EAGLE yields with a transition to I^2 scaling so as not to exceed 25% of the kinetic energy.

Two sets of calculations have been completed. The first set of calculations was completed to assess the impact of changing the implosion time from 400 ns to 250 ns on the pulsed power driver from the water output line to the load. The second set of calculations was done to determine the optimum inductance for the front-end to minimize pulsed power risk and maximize current (radiation yield).

A sketch of the baseline front-end configuration for driving a PRS load is shown in Figure 9. This configuration utilizes most of the MITL hardware that is being built for the bremsstrahlung load configuration. This design consists of a transition from coax to triplate, a conventional two-sided post-hole convolute and a PRS load. The inductance for the DQ from the end of the output water-line through the initial inductance of the load is 35 nh (oil line-7 nh, tube-5 nh, PFL MITL-7 nh, transition MITL- 5 nh, triplate MITL-5 nh, convolute and load-6 nh).

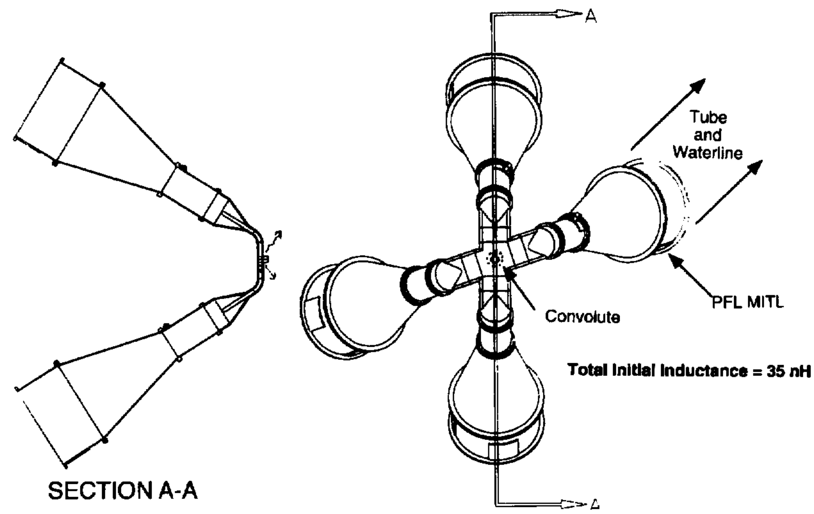


Figure 9. Decade Quad direct drive PRS configuration (uses the Brems MITLs).

The results of the design calculations for the 400 ns implosion time case are shown in Figure 10. The peak current delivered to the PRS load is 7.4 MA, the total kinetic energy delivered to the load is 370 kJ and the estimated argon k-line yield is 90 kJ. The other plots in this figure show an assessment of the power flow risk at two locations in the vacuum section of the machine. Figure 10(b) shows the two critical power flow parameters at the location of the convolute: the load impedance V/I divided by the geometric impedance and the electric field as functions of time. The engineering design criteria are marked on these two plots. The convolute is well magnetically insulated throughout the entire implosion process. The electric field exceeds field emission near the time of implosion however the electron losses should be low as evidenced by the magnetic insulation plot. Figure 10(c) shows the power flow conditions at the location of the PFL MITL. Near the beginning of the pulse the PFL is not well insulated since there is voltage but low current, however the electric field is below the emission threshold so there should be no significant losses. Note that once the field exceeds field emission the MITL is well insulated.

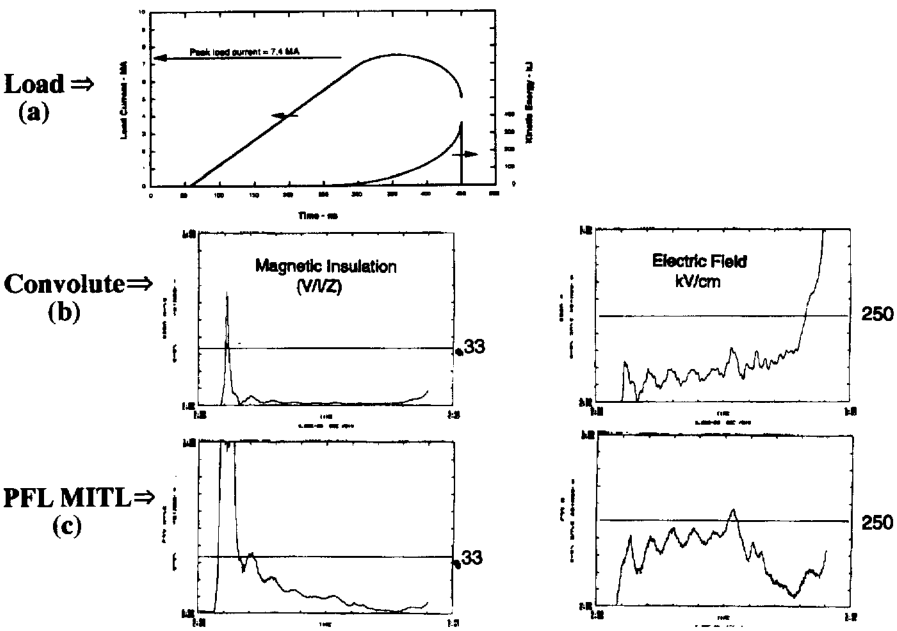


Figure 10. Case 1, 400 ns implosion time, delivers 7.4 MA peak current to the PRS for 370 kJ of kinetic energy and a predicted argon yield of 90 kJ.

The results of the design calculations for the 250 ns implosion time case are shown in Figure 11. The peak current is 5.6 MA and the kinetic energy delivered to the load is 245 kJ with the estimated argon k-line yield of 60 kJ. The assessment of the power flow in the convolute and in the PFL MITL is shown in Figure 11(b and c). Near the time of implosion the magnetic insulation is much closer to breakdown than the previous case of a 400 ns implosion time. The increased stress on the MITL is due to the application of the implosion voltage (I x Ldot) at a much lower current in the MITL. Note that it is important to design the MITL conservatively for a 400 ns implosion time load to allow the flexibility to also drive a shorter 250 ns implosion time load.

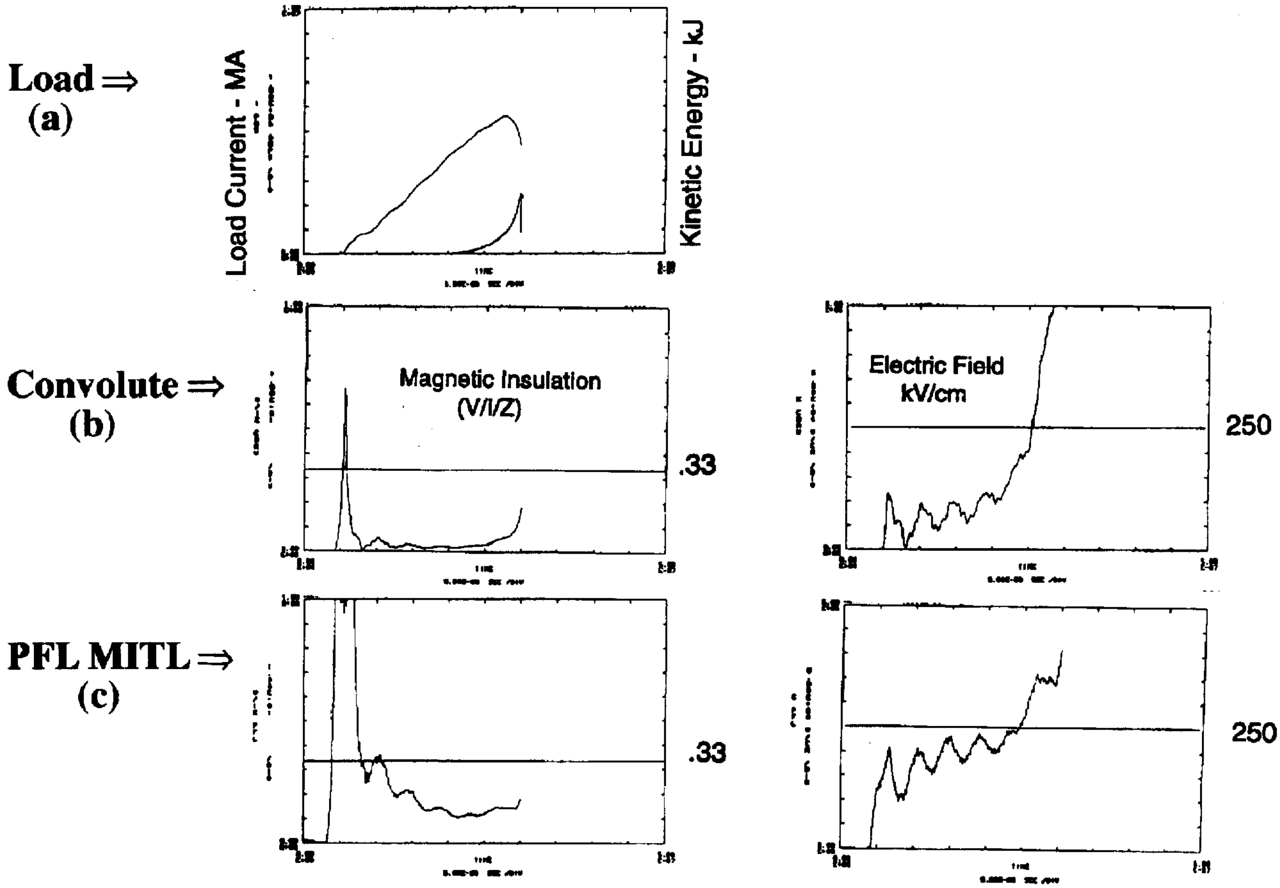


Figure 11. Case 2, 250 ns, implosion time, delivers 5.6 MA peak current to the PRS load for 245 kJ of kinetic energy and a predicted argon yield of 60 kJ.

A final set of model calculations was performed to determine the sensitivity of the radiation output to the front-end inductance. The inductance was scanned from the 35 nh baseline case down to 11 nh. Note there was no self-consistent machine design for the inductances less than 35 nh. The purpose of this set of model calculations was to determine the minimum inductance goal for the front-end for achieving the maximum radiated yield (in the model radiated yield is represented by the kinetic energy delivered to the load). The results of these calculations are shown in Figure 12. The 17 nh case is the minimum inductance for achieving most of the available kinetic energy. Reducing the inductance to 11 nh increases the kinetic energy by only 2%. The goal for future front-end pulsed power designs is to reduce the inductance from the 35 nh to 17 nh without increasing the power flow risk or reducing the flexibility to drive 400 ns to 250 ns implosion time loads.

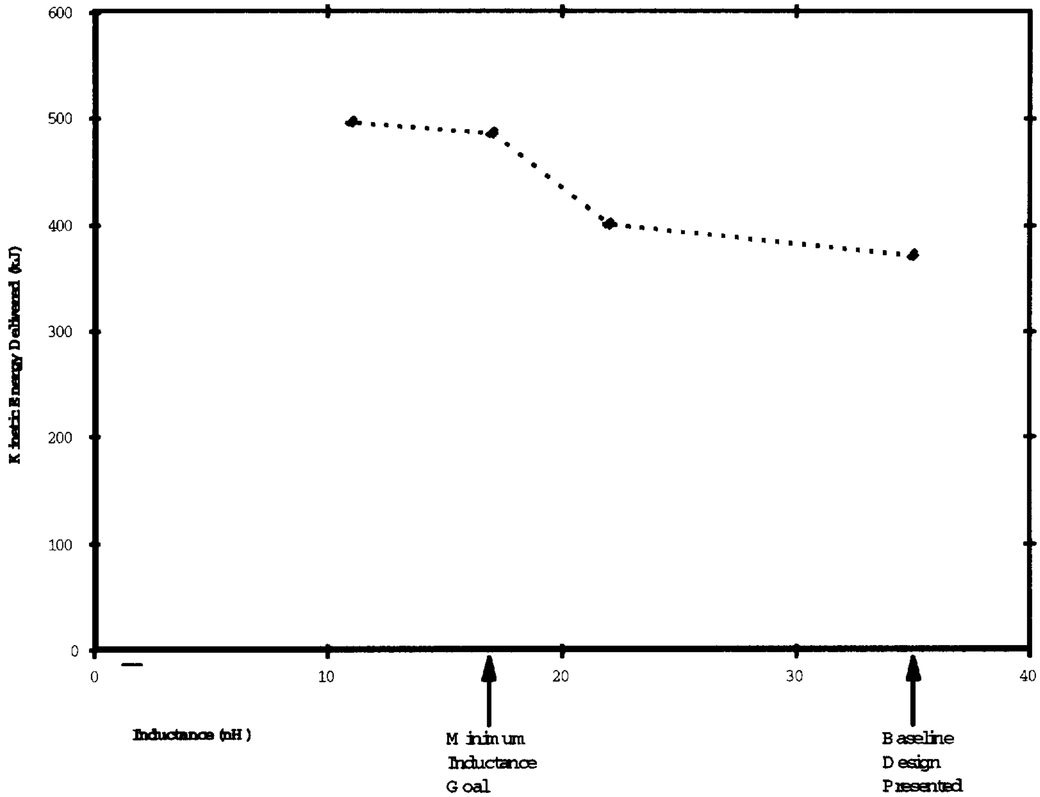


Figure 12. Performed a circuit scan to determine the optimum inductance for maximum kinetic energy.

CONCLUSION

The Decade Quad four module facility will be built at AEDC in Tennessee by the spring of 1999. The facility will initially drive large area (2250 cm^2) bremsstrahlung diode loads. Two full power prototype modules have been built and tested into electron beam bremsstrahlung loads. Over 3500 machine shots have been taken on the two modules. The measured pulsed power and the radiation output performance from the single module have been used to predict the radiation output from the Decade Quad. The new machine will be capable of producing 16 krads(Si) over a 2250 cm^2 test area with a 47 ns radiation pulse width.

A 35 nH system design for the Decade Quad with an imploding plasma as the load has been completed. The electrical stress on the critical pulsed power components has been assessed for two implosion times (400 ns and 250 ns). The results of these assessments show the convolute and MITL must be conservatively designed at the 400 ns implosion time to be capable of driving loads at the 250 ns implosion time. The baseline 35 nh design will be capable of delivering 370 kJ of kinetic energy to the PRS load.

The results of the circuit model calculations at lower inductance show there is a minimum of about 17 nh that will deliver the maximum kinetic energy to the load. Pulsed power designs with lower than 17 nh will produce only slightly higher kinetic energy and will add risk of failure in the power flow of the system.

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REFERENCES

1. Meger, R. J. Commisso, G. Cooperstein, and S. A. Goldstein, Appl. Phys. Lett. 42, 943 (1983).
2. B. V. Weber, R. J. Commisso, G. Cooperstein, J. M. Grossmann, D. D. Hinshelwood, D. Mosher, J. M. Neri, P. F. Ottinger, and S. J. Stephanakis, IEEE Trans. Plasma Sci. PS-15 (1987); see also Ref 5.
3. G. A. Mesyats, S. P. Bugaev, A. A. Kim, B. M. Koval'chuk, and V. A. Kokshenov, IEEE Trans. Plasma Sci. PS-15 (1987).
4. C. W. Mendel, Jr., M. E. Savage, D. M. Zagar, W. W. Simpson, T. W. Grasser, and J. P. Quintenz, J. Appl. Phys. 71, 3731 (1992).
5. R. J. Commisso, P. J. Goodrich, J. M. Grossmann, D. D. Hinshelwood, P. F. Ottinger, and B. V. Wever, Phys. Fluids B 4, 2368 (1992).
6. R. R. Goyer, D. Kortbawi, P. S. Sincerny, D. Parks, and E. Waismann, J. Appl. Phys. 77(6), 2309 (1995).
7. W. Rix, D. Parks, J. Shannon, J. Thompson, and E. Waismann, IEEE Trans. Plasma Sci 19 (1991)
8. P. Sincerny, S. Ashby, K. Childers, C. Deeney, D. Drury, J. Goyer, D. Kortbawi, I. Roth, C. Stallings, L. Schlitt, 9th IEEE Pulsed Power Conf., Alb., NM, IEEE 93CH3350-6, 880 (1993).
9. P. Sincerny et al, 10th IEEE Pulsed Power Conference, Alb., NM, IEEE 95CH35833, LOC #95-78039, PY05 (1995).
10. Weber et al Paper from this the 11th Pulsed Power Conf.